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Ins B1

~~PHOTODETECTOR CIRCUIT~~

Ins B2

This invention relates to a photodetector circuit.

Ins B3

Semiconductor photodetectors based on the silicon bandgap are suitable for operation in the visible and near infrared region of the spectrum. Prior art silicon photodetectors can be constructed in compact form and cheaply using mature CMOS technology. Photon illumination of a photodiode results in the generation of an electrical current, the photocurrent. It is desirable for many applications for the photodetector to be responsive to a very wide range of input intensities. This is facilitated by passing the photocurrent through a MOSFET load device operating in its subthreshold regime. In this regime, MOSFET output (voltage) response is a logarithmic function of its input (current). Thus the combined photodiode/MOSFET device has a logarithmic illumination versus output voltage characteristic. The dynamic range of the overall system is very large: detectable illumination may vary by as much as 5 or 6 orders of magnitude.

A problem with such prior art devices is that the MOSFETs have inherent leakage currents which represent a substantially constant loss in a stable environment. There are two consequences of this leakage current which significantly limit conditions under which such CMOS photodetecting circuits can be operated effectively. First, although leakage current is not a significant problem in high illumination intensity when the MOSFET is operated at current levels far larger than the leakage level, it can severely degrade detector sensitivity at low light levels. Secondly, leakage current is highly temperature dependent and increases severely at elevated temperatures. While the first of these problems has been widely addressed in the prior art, the second has received little attention.

Very low light sensitivity has been improved by moving from pure CMOS to parasitic bipolar circuitry within a CMOS process. For example, Mead in Analog VLSI and Neural Systems, Addison-Wesley 1989, p218 - 219 and p260 - 261, describes such a photodetector circuit. The photodiode is replaced with a bipolar transistor with gain β. This amplification characteristic raises the low level visibility "approximately to a moonlit scene focused on the chip through a standard camera lens". However,

where low light levels are of particular interest, problems still remain. For example, US patent 5 097 305 to Mead addresses this problem. Mead discloses a phototransistor whose photocurrent is, following the usual practice, read instantaneously at higher values, but readout charge is integrated at the low end of the photocurrent scale. Similarly, US patent 5 155 353 to Pahr, is concerned with reducing the susceptibility to noise of photodetector circuits employing either phototransistors or photodiodes, which again is more problematic at low-light levels. Thus, while these phototransistor circuits may have some specialist applications, the fact remains that the cheaper and more compact pure CMOS devices work acceptably well down to twilight illumination levels and the adaptation is not generally worthwhile.

A more fundamental obstacle to the general portability of CMOS photodetectors is their temperature instability, noted above. This is potentially a serious barrier to the commercial uptake of CMOS detectors in instruments designed to respond to everyday light levels, such as the recently developed digital cameras. This is despite the inherent cost and performance advantage offered by CMOS over currently used CCD detectors. There is a perceived market for a single camera which operates effectively in the variety of environments and throughout the whole range of illumination levels to be anticipated by the modern photographer.

The low-light sensitivity of pure CMOS photodetectors has been improved by operating at low temperatures and exploiting the consequent reduction in leakage current. However cooling apparatus e.g. Peltier cooler or dewar, is bulky and represents a significant drain on power sources, proving inconvenient to numerous applications.

INS B1

It is the object of this invention to provide a photodetector with improved temperature stability.

The present invention provides a substantially temperature-insensitive photodetector circuit characterised in that it incorporates photon detecting means arranged to produce an electric current in response to incident photon illumination associated

with a current load device arranged to produce a voltage response to current flow wherein

(a) the photon detecting means is arranged to provide an output current which is supplied to the current load device,

(b) the current load device has a current-voltage characteristic in which the voltage is a logarithmic function of current flow, and

(c) the photon detecting means is a phototransistor with a current gain factor greater than unity.

In an alternative aspect, this invention provides a photodetector circuit incorporating photon detecting means arranged to produce an electric current in response to incident photon illumination associated with a current load device arranged to produce a voltage response to current flow wherein

(a) the photon detecting means is arranged to provide an output current which is supplied to the current load device,

(b) the current load device has a current-voltage characteristic in which the voltage is a logarithmic function of current flow,

(c) the photon detecting means is a phototransistor with a current gain factor greater than unity, and

(d) the circuit is substantially insensitive to temperature over a range of light intensity and temperature normally to be encountered in a daytime natural environment.

This invention provides the advantage of improved temperature stability compared to prior art photodetecting devices which are also capable of responding to a large dynamic range of incident illumination intensities. The gain of the phototransistor acts on the generated photocurrent to produce a far larger output current in comparison with that generated by a comparable *p-n* photodiode. This amplification of the current supplied to the current load device ensures that current within the load is generally much higher than the leakage current, even at elevated temperatures and yet still maintains the load logarithmic voltage response. Leakage current therefore represents only a small loss from the perceived photocurrent and accurate intensity measurements of normal illumination levels can be made at relatively high temperature.

The invention also, as an additional effect, improves the low-illumination level response of a photodetector circuit in comparison with CMOS circuitry. This is in contrast to prior art disclosures in which the actual sought after effect is extension of the low-illumination limit of CMOS. A further, inherent, advantage arises in improving temperature stability in the manner of this invention, which is improvement in signal to noise ratio. A major contribution to noise depends on charge carrier concentration and therefore also on magnitude of leakage current; signal to noise ratio is degraded by an increase in leakage current, but it is improved if the signal is amplified above the leakage current level in accordance with the invention.

This invention has numerous applications to imaging objects used in everyday environments, which can typically be expected to vary in temperature. In a particularly preferred embodiment, the invention is incorporated in a digital camera, of the kind now becoming ever more popular despite the disadvantages of CCD detectors currently used therein. Modern day travellers expect such a camera to last a number of trips, and to serve them well across a variety of temperature and light conditions They require a lightweight camera capable of imaging acceptably all areas of a scene at temperature extremes in both hot and cold climates.

Specifically, the phototransistor and current load device may be arranged to provide an output signal including a contribution from leakage current and a contribution responsive to incident illumination and the latter contribution exceeds the former at all normal operating temperatures of the circuit such that the circuit is substantially temperature-insensitive.

In a preferred embodiment, the phototransistor and current load device are fabricated using BiCMOS technology. BiCMOS is an optimised technology covering fabrication of both bipolar and CMOS devices which thus gives the advantage of versatility. The phototransistor and load device may therefore be of any type (e.g. FET, npn, pnp, etc.), and fabricated in the same process. Other considerations may thus be taken into account in specific applications in order to determine the most appropriate implementation of this embodiment of the invention.

The current load device may be a MOSFET device with its source or drain connected to the phototransistor and the phototransistor is arranged to produce an electric current which is low enough to operate the MOSFET in its subthreshold regime. This provides the advantage of economy. A MOSFET operating subthreshold provides the desired logarithmic output with which to extend the dynamic range of a photodiode or phototransistor. The MOSFET can be fabricated using CMOS technology, the state of which is such as to permit relatively cheap fabrication.

The phototransistor is preferably a bipolar transistor incorporating a photodetecting base region and with emitter connected to the load MOSFET. Such a bipolar phototransistor provides the required photosensitivity and has high amplification: the output current can be larger by a factor of ~ 100 in comparison with a *p-n* junction photocurrent. FET phototransistors do not generally exhibit the same degree of gain and therefore cannot raise the signal above the transistor leakage level over such a wide temperature range. Furthermore a bipolar transistor may provide the advantage that the circuit is relatively easily fabricated. Such transistors may be manufactured in CMOS as a natural by-product of the bulk process. Generally, these lateral or vertical bipolar transistors are considered parasitic, as they may lead to problems in standard logic circuits. However, their photodetecting capability makes them ideally suited to this application.

In an alternative aspect, this invention provides a substantially temperature-insensitive photodetector circuit characterised in that it includes a bipolar phototransistor, a load MOSFET and voltage detecting means wherein:

(a) the bipolar phototransistor is arranged to supply photocurrent output to the load MOSFET,

(b) the phototransistor is arranged such that photocurrent output is sufficiently small to maintain subthreshold operation of the load MOSFET, and

(c) voltage detecting means is arranged to detect a voltage output from the load MOSFET in response to photocurrent supply.

In a preferred embodiment, the phototransistor and current load device are fabricated using BiCMOS technology.

As noted above, bipolar phototransistors may result from the CMOS fabrication process as parasitic devices. However, this is not ideal as such devices are not optimised on a standard CMOS process. Although they may be suitable for some applications, these bipolar phototransistors are large and have low matching. The former feature forces the detector designer to accept either poor pixel spatial resolution or an expensive requirement for a physically large array. The latter feature leads to high fixed pattern noise. However, as a fabrication process, BiCMOS provides the advantage that it affords a compromise between these extremes. BiCMOS is optimised both for CMOS and bipolar device manufacture, making it eminently suitable for application to devices requiring both device types. When compared with parasitic bipolar technology therefore BiCMOS provides the advantages of higher spatial resolution and reduced fixed pattern noise. Fixed pattern noise arises in array circuits in which the response characteristics of individual circuit elements differ across the array (low matching). This introduces a noise level caused by unequal responses to the same illumination. However bipolar transistors can be fabricated more uniformly in BiCMOS, giving rise to a reduction in fixed pattern noise.

Furthermore, BiCMOS allows the readout circuit to be made with lower noise that an equivalent CMOS circuit, thus increasing the performance of the photodetecting system still further.

Specifically, the photodetector may be for the purpose of operation in environmental temperatures ranging from -20 to 60°C with substantially unaffected sensitivity at illumination levels down to 1 lux. This provides the advantage that the detector is suitable for application in most natural conditions of illumination and temperature.

The photodetector circuit may incorporate an attenuator arranged to reduce the intensity of light prior to incidence on the photon detecting means to an extent necessary to provide for the resultant output current to be low enough to operate the MOSFET in its subthreshold regime. This provides the advantage of flexibility. The upper end of the phototransistor dynamic range may, in high-illumination situations, result in a photocurrent sufficiently large that it pushes the MOSFET out of its

saturation regime, and the logarithmic response of the circuit will be lost. The use of an attenuator guards against this eventuality.

In particular, the photodetector may be capable of operation in environmental temperatures ranging from -20 to 60°C with substantially constant contrast sensitivity.

In a preferred embodiment the load MOSFET and phototransistor are connected at a common connection point to buffering means and the buffering means is connected to a pixel readout circuit.

The photodetector circuit may be incorporated in an array of like circuits. This provides the advantages generally to be had from an array of imaging pixels.

Alternatively, an embodiment of the invention provides a detector array of photodetector circuits each of which may be in accordance with an aspect or embodiment described above.

A further embodiment provides a digital camera incorporating an array of photodetector circuits each of which may be in accordance with an aspect or embodiment of the invention described herein.

A further aspect of this invention provides a digital camera incorporating an array of photodetector circuits characterised in that each circuit incorporates photon detecting means arranged to produce an electric current in response to incident photon illumination associated with a current load device arranged to produce a voltage response to current flow, and wherein

(a) each circuit is of BiCMOS construction,
(b) the photon detecting means is arranged to provide an output current which is supplied to the current load device,
(c) the current load device has a current-voltage characteristic in which the voltage is a logarithmic function of current flow,
(d) the photon detecting means is a phototransistor with a current gain factor greater than unity, and

(e) the phototransistor and current load device are arranged to provide an output signal including a contribution from leakage current and a contribution responsive to incident illumination and the latter contribution exceeds the former at all normal operating temperatures of the circuit such that the circuit is substantially temperature-insensitive.

Further embodiments of this invention may provide an apparatus comprising hand-held computer technology or a personal digital assistant incorporating an array of photodetector circuits each in accordance with an aspect or embodiment of the invention described herein.

With developing technology, digital cameras are being included in a number of compact devices. For example personal digital assistants ("pda"s or "palm top computers") often incorporate such a camera to increase their functionality. Clearly, to increase portability without losing functionality it is desirable to have as compact and as lightweight an imaging system as possible. Furthermore, many users will travel with their pda, which could be essential to their business concerns. There is thus a requirement that the imaging function of such devices will operate effectively over a range of world temperatures and climates.

A car may incorporate a digital camera and signal processing means wherein the signal processing means is arranged to analyse data received from the digital camera and assist in car control. This is advantageous to safe driving. The digital camera may be installed next to a car driver and used to provide, for example, advanced cruise control. The camera can be set up to detect, for example, another car pulling out in front. The signal processing can then be arranged to respond to the hazard and control the car (for example, apply the brakes) accordingly.

Of primary importance to any such safety mechanism is that it can be relied upon at all times. Thus, although a stable temperature will be reached after some time driving, it is necessary to ensure that the imaging capability is adequate at start up. Cars may be, and often are, parked in a variety of weather conditions and the temperature can consequently be very hot, very cold or anywhere intermediate these extremes at start up. By using a digital camera incorporating the temperature-

insensitive photodetector circuit of this invention, reliable operation over the required temperature range can be achieved.

In another aspect, this invention provides a substantially temperature-insensitive method of measuring photon radiation intensity over a dynamic range greater than four orders of magnitude characterised in that the method comprises the steps of:

(a) providing a photodetector circuit comprising a bipolar phototransistor arranged to supply output current to a load MOSFET,

(b) arranging the phototransistor to respond to incident radiation by providing output current to operate the load MOSFET subthreshold,

(c) detecting the load MOSFET output voltage response to said output current.

Preferably, the photodetector circuit of Step (a) is fabricated in BiCMOS.

In order that the invention might be more fully understood, an embodiment thereof will now be described with reference to the accompanying drawings in which:

Figure 1 is a circuit diagram of a prior art photodetector pixel.

Figure 2 is circuit diagram of a photodetector pixel of the invention.

Figure 3 is a schematic illustration of a digital camera incorporating an array of photodetector pixels of the invention.

With reference to *Figure 1*, a pixel of a prior art photodetector circuit is illustrated generally by 10. This photodetector pixel 10 is suitable for incorporation in an array of like pixels to create a detector array. The photodetector pixel 10 comprises a photodiode 12 and load metal oxide field effect transistor (MOSFET) 14 connected via MOSFET source 16 at connection node 18. The MOSFET 14 also has drain connected to both gate and power supply V_{DD} and therefore constitutes a load for the photodiode 12. In this arrangement light 20 incident on the photodiode 12 results in a photocurrent I_{ph} and voltage V_{ph} being developed at the connection 18. This connection 18 is buffered from a constant current sink (not shown) by a second MOSFET 22. The second MOSFET 22 has gate 24 connected to the connection 18,

drain 26 connected to the power supply V_{DD} and source 28 to a MOSFET switch 30. It thus constitutes a source-follower driver. A switch voltage (V_{sw}) may be applied to a MOSFET gate 32 in order to operate the MOSFET switch 30. This provides for an output voltage (V_{out}) to develop at a pixel output line 34 which is connected to an array readout circuit (not shown).

Figure 2 illustrates a photodetector pixel circuit of the invention, indicated generally by 100. This photodetector pixel 100 comprises a number of components which are common to the prior art device 10. Such components are referenced by numbers 100 greater than the corresponding references in *Figure 1* and include: a load MOSFET 114 with source 116 connected to connection node 118 and drain and gate connected as for *Figure 1*; second MOSFET 122 with gate 124, drain 126 and source 128 connected as for *Figure 1*; switching MOSFET 130 addressed via its gate 132; and pixel output line 134. The photodetector pixel of the invention 100 also includes a bipolar phototransistor 200. The bipolar phototransistor 200 has its emitter connected to connection node 118.

With reference to *Figure 1*, the operation of the prior art photodetector pixel 10 will now be described. Light 20 incident on the photodiode 12 results in the generation of photocurrent I_{ph}. This current is constrained to flow as the source-drain current of the load MOSFET 14 by virtue of its isolation from the remainder of the circuit by the second MOSFET 22. A fraction of this photocurrent is however lost from the MOSFET 14 as a leakage current $I_{leakage}$, and the MOSFET 14 actually operates at an input channel current I_{ch}. In consequence of this channel current I_{ch}, a voltage difference (V_{gs}) develops between gate and source of the load MOSFET 14 to the extent necessary to operate the load MOSFET 14 at this current I_{ch}. This voltage difference V_{gs} is attained by driving a voltage at the MOSFET source 16 to a value V_{ph} ($\cong V_{DD}$ - V_{gs}). This voltage V_{ph} is therefore that appearing on the connection node 18, which contains information regarding illumination intensity and which is consequently termed the photovoltage. The photodetector 12 is constructed such that over a range of expected illumination intensities, the generated photocurrent (I_{ph}) is much less than that needed to drive the voltage difference V_{gs} above the load MOSFET threshold voltage. The MOSFET 14 therefore operates in its subthreshold regime. In this regime, a MOSFET drain current (I_d) is an exponential function of its

gate-source voltage difference (V_{gs}) and therefore also of its source voltage (V_s): $I_d \propto \exp(V_s)$. In the photodetector circuit 10, the gate voltage is held at V_{DD} and the source voltage is the photovoltage V_{ph} developed at connection 18. The drain current is the channel current I_{ch}, and so:

$$I_{ch} \propto \exp(V_{ph})$$

$$\Rightarrow V_{ph} \propto \ln I_{ch}$$

$$\text{and } V_{ph} \propto \ln (I_{ph} - I_{leakage})$$

Thus, if the leakage current is negligible in comparison with the generated photocurrent, the photovoltage is proportional to the logarithm of the photocurrent response: $V_{ph} \propto \ln I_{ph}$.

The voltage V_{ph} generated at connection 18 is applied to the gate 24 of the second MOSFET 22. The drain-source current of this MOSFET 22 is constant, constrained by the constant current sink. The voltage (V_{sf}) at the source 28 of this MOSFET 22 therefore follows any variation in the gate voltage (photovoltage V_{ph}) in order to maintain this constant current. The MOSFET 22 thus functions as a source-follower driver: $V_{sf} = V_{ph} - \Delta$, where Δ is the voltage drop required to operate the MOSFET at the current provided by the constant current sink. This MOSFET 22 isolates the connection node 18 and therefore provides a buffering capability between the connection node 18 and readout circuit. The voltage (V_{ph}) at connection 18 is thus free to vary in accordance with the photocurrent (I_{ph}) with negligible influence from the readout circuit. In summary, the MOSFET 22 drives its source voltage V_{sf} to follow the photovoltage V_{ph}, a logarithmic function of the photocurrent I_{ph}.

Switching MOSFET 30 acts to switch a voltage on the source 28 of the second MOSFET 22 to the pixel output line 34, the output line 34 being shared by several pixels. Application of an appropriate voltage (V_{sw}) to the gate 32 turns the switching MOSFET 30 ON and whatever voltage is present on the source 28 of the second MOSFET 22 is passed substantially unaffected to the pixel output line 34 as output voltage V_{out}. In this way, a pixel is addressed via a voltage (V_{sw}) to the switching MOSFET 30 which enables the output voltage (V_{out}) to be read by the readout circuit. This output voltage (V_{out}) is a measure of the photovoltage (V_{ph}) developed at the

load MOSFET source 16 in response to illumination of the photodiode 12. In particular:

$$V_{out} \cong V_{sf} = V_{ph} - \Delta, \text{ and}$$

$$V_{ph} \propto \ln (I_{ph} - I_{leakage})$$

In situations in which the leakage current is negligible, the prior art photodetector pixel 10 thus produces an addressable output voltage which is a measure of the logarithm of the input illumination intensity.

If the leakage current is not negligible the prior art photodetector sensitivity is reduced. In some working environments e.g. an air-conditioned office, the temperature is generally sufficiently stable and cool and the illumination intensity adequately high that no significant reduction in sensitivity occurs. However, at higher temperatures leakage current increases dramatically and picture quality in darker areas of even a standard scene may be severely degraded. Thus prior art CMOS imagers are not appropriate if required to be used in differing environments or in those for which a variety of ambient temperatures are anticipated.

With reference to *Figure 2*, the operation of the photodetector pixel of the invention will now be described. The bipolar phototransistor 200 provides an output current I_{bi} which is a measure of incident light 120 intensity. Bipolar phototransistors are known in the prior art. They behave essentially as standard bipolar transistors but the base signal is generated by photon illumination. The base current is similar in magnitude to that of a photodiode fabricated from identical materials. The collector current is equal to the base current multiplied by the transistor gain factor β. A typical phototransistor structure has a β value of around 100. Thus, in this invention, the current output from the phototransistor 200 is given by

$$I_{bi} \cong \beta I'_{ph}$$

where I'_{ph} is the current which is generated by a photodiode fabricated from the same base-emitter material.

Illumination of phototransistor 200 therefore results in the generation of a bipolar photocurrent I_{bi}. Thereafter, operation of many components of *Figure 2* are similar to those of *Figure 1*. Voltages generated which are analogous to those within the prior

art photodetector pixel 10 but dependent on bipolar current I_{bl} as opposed to I_{ph} will be indicated as such by the use of the previous symbol primed. The bipolar photocurrent I_{bl} is constrained to flow as the source-drain current of the load MOSFET 114. The gate-source voltage of the MOSFET 114 is raised to a level consistent with the actual channel current: the bipolar photocurrent I_{bl} less an amount lost as MOSFET leakage current $I'_{leakage}$, which causes a voltage V'_{ph} to develop at connection node 118. The bipolar photocurrent operates the MOSFET 114 in its subthreshold regime and so $V'_{ph} \propto \ln (I_{bl} - I'_{leakage})$. The second MOSFET 122 is configured as a source-follower driver and so V'_{ph} is passed from its gate connection with connection 118 to source 128, less an offset Δ'. This source voltage is passed to the pixel output line 134 as V'_{out} on activation of the switching MOSFET 130. Thus the photodetector pixel 100 of the invention provides an addressable output voltage which is given by

$$V'_{out} \cong V'_{ph} - \Delta', \text{ and}$$

$$V'_{ph} \propto \ln (I_{bl} - I'_{leakage}),$$

and which is therefore a measure of the logarithm of the input illumination intensity. In this invention however, the phototransistor current is a factor of ~ 100 larger than the equivalent photodiode current generated in the prior art device:

$$V'_{ph} \propto \ln (\beta I'_{ph} - I'_{leakage}),\ \beta \sim 100$$

In both photodetector pixel circuits 10, 100 herein described, the leakage current occurs at the load MOSFET 14, 114. This leakage is a significant proportion of the photocurrent if the photocurrent is at the low end of its range i.e. low illumination and/or high operating temperature. By using a phototransistor in place of a conventional photodiode the photocurrent is magnified by a gain factor β which appears to the pixel circuit to be equivalent to an increased photocurrent. This larger current through the load MOSFET 114 effectively raises the operating regime of the load MOSFET 114 above problematic leakage levels. Variations in the leakage current $I'_{leakage}$ due to temperature fluctuations will not significantly affect $\beta I'_{ph}$, despite an order of magnitude equivalence between I'_{ph} and $I'_{leakage}$. The circuit 100 is therefore substantially temperature insensitive in its normal operating conditions which, for the purposes of this specification, means that the amplified

photocurrent (*$\beta I'_{ph}$*) is larger than the leakage current (*$I'_{leakage}$*) for circuit operating temperatures from -20°C to 60°C.

The photodetector circuit 100 of the invention is fabricated in BiCMOS technology. BiCMOS is optimised for both bipolar and CMOS technology but it is significantly more expensive to implement than CMOS. For most applications the expense of BiCMOS cannot be justified and its adoption is not normally considered.

However, an application of the BiCMOS circuit of the invention is illustrated in *Figure 3*. Shown in *Figure 3* are the optical components of a digital camera, illustrated generally by 300. The camera 300 contains an objective lens 305 which focuses light, indicated generally by ray paths (310a, 310b, 310c, 310d), from a scene (not shown) onto a detector array 315. The detector array 315 comprises an array of photodetecting pixels 100 of the type illustrated in *Figure 2*. Each pixel 100 is addressable and its voltage measurable via readout lines, e.g. 320a, b. The camera optic axis 330 is also illustrated.

The intensity of radiation at each pixel site is indicated by the voltage measured via the readout lines 320a, b. An image of the scene can therefore be represented as an array of voltage values. Standard cameras produce intensity representations of the observed scene. Digital cameras however store measured voltage values digitally and therefore permit their manipulation within signal processing circuitry. Such manipulated voltage values may then be used to create an amended (enhanced, or otherwise) image of the original scene.

The resolution of the detector array 315 depends on the spacing of the pixels. However parasitic bipolar phototransistors resulting from the CMOS fabrication process are large and have low matching. Use of BiCMOS results in smaller bipolar transistor elements with better matching. Thus the advantages to be gained in reducing the temperature sensitivity of large dynamic range photodetectors while still maintaining accurate pixel resolution justify this surprising application of BiCMOS.

Although the embodiment of a detector array herein described was referred to a digital camera, the detector array may also be used in other imaging equipment for which a lightweight camera is desired and digital image representation required.

It will be appreciated by one skilled in the art of circuit design that only one embodiment of the circuit of the invention is described herein and the invention may be equivalently implemented in a variety of bipolar transistor - MOSFET combinations. In this embodiment a pnp phototransistor is illustrated with an NMOS load. Both pnp and npn phototransistors may be used in combination with either NMOS or PMOS loads to produce the temperature-robust photodetector of the invention. Preference for a particular combination may be for a variety of reasons - a likely consideration will be the way in which the BiCMOS fabrication process is implemented.

In another embodiment, an intensity attenuator is incorporated in the invention. This enables the photodetector 100 to function comparably with prior art devices at high illumination intensities. The attenuator is arranged to reduce the incident light intensity in high-illumination situations prior to its detection by the phototransistor. This effectively raises the illumination upper threshold at which the pixel circuit 100 can operate. This is necessary to maintain load MOSFET 114 operation in its subthreshold region. There is a maximum MOSFET current limit, above which the characteristic is no longer logarithmic and saturation begins to occur. This embodiment of the invention effectively shifts this upper limit to a higher illumination. This maintains a large operating range despite gain being included in the photodetector to counteract performance degradation in variable temperature environments. The attenuation may be provided by, for example, reducing the photodetector lens aperture.